#### APPENDIX I

**Temperature** 

#### Appendix I: Temperature

Section	<u>Page</u>
Basic Concepts	I-2
Temperature Measurements	I-8
Spoke Strains and Temperature	I-21
Heating and Cooling of Discs	I-36

### **Basic Concepts**

### **Ambient Temperatures**

- Temperatures Measured On The Disc Are The Combined Effect Of The Heating Of The Disc During Braking And Ambient Temperature
- Ambient Temperatures For Each Test Day Are Provided In The Following Table

Table I.1. Ambient Temperatures Over The Test Days At 4 Primary Locations

Temperatures on the test days						
Day	Wash DC	Philadelphia	New York	Boston	Max-Min	
16th May	65	68	63	50	18	
17th May	68	70	63	58	12	
26th May	70	58	60	53	17	
27th May	80	82	76	59	23	
17th Jun	75	70	71	58	17	
18th Jun	80	75	74	56	24	

Note: Temperatures Noted Above Are Approximately The Ambient Temperatures At The Locations Listed When Trainset 10 Arrived At The Station

Source: www.wunderground.com

### Disc Expansion Model

- Simple Model To Determine Reasonable Values Of Mean Spoke Strain Due To Temperature Increase of Friction Rings
- Based on Friction Ring Unrestrained Expansion
- Assumes Spokes Follow Friction Ring

# Thermal Expansion of Friction Rings

Circumference of friction plate expands with increased temperature  $\alpha$  = coefficient of thermal expansion

$$C(T) = C_0(1 + \alpha T)$$

 $R_0$  Radius at point A

R Radius at point A with increased temperature

$$(R-R_0) = C_0 \alpha T / 2\pi$$

Strain in Spoke of Length L due to temperature change

$$(R - R_0)/L = C_0 \alpha T/2\pi L$$
 = Tensile Strain

L = Length of Spoke

## Thermal Expansion of Friction Rings

- $C_o = 67$  inches
- L = 7 inches
- A=7\*10<sup>-6</sup>/degree F
- Spoke Strain/Degree F = 10.7μ Strain / F°
- Spoke Resists Expansion, So The Resulting Strain In Spoke Should Be Less Than This Value

### Temperature Measurements

### Temperature Measurements

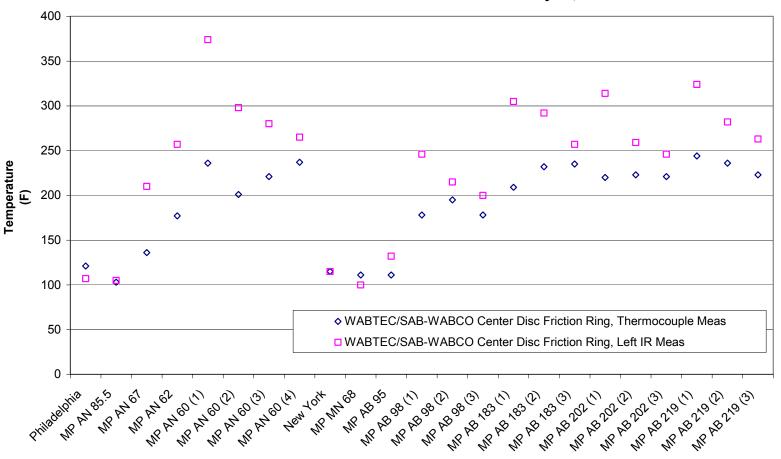
- Two Types of Temperature Sensors were used during Testing
  - IR Sensors
  - Thermocouples
- The IR sensors were aimed at the friction surface at approximately a 90 Degree Angle

### Temperature Sensors

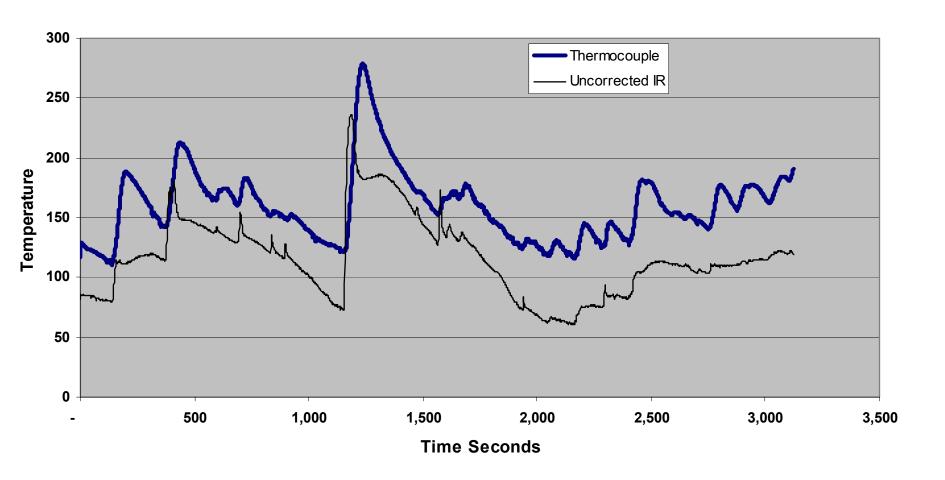
- IR Sensor
  - Aimed At Friction Surface
  - Non-contact
  - Fast Response
- Thermocouple
  - Attached To Back Of Friction Surface
  - Rotates With Axle
  - Slow Response Requires Back Of Friction
     Plate To Heat Up

### Comparison of IR and Hand Thermocouple Measurements

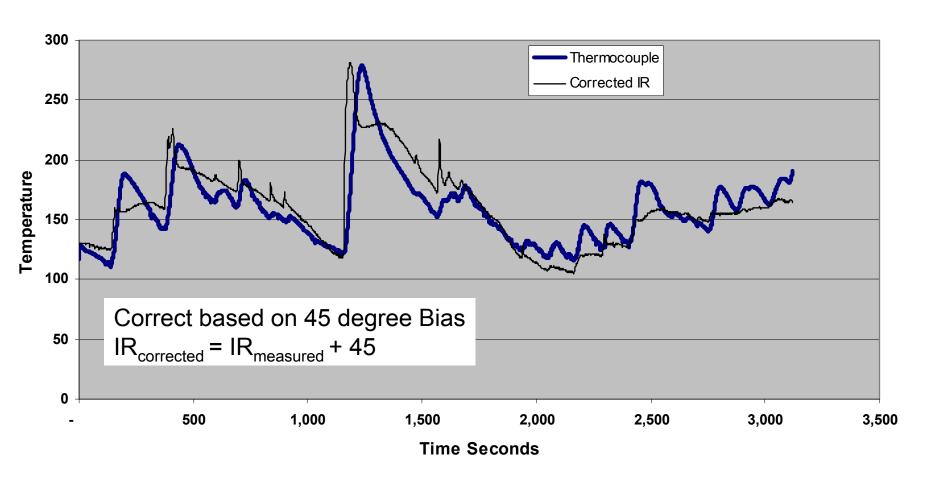
Comparison of "Hand" Thermocouple Measurements with IR Temperature Measurement, Left Side of Center WABTEC/SAB-WABCO Disc - May 16, 2005



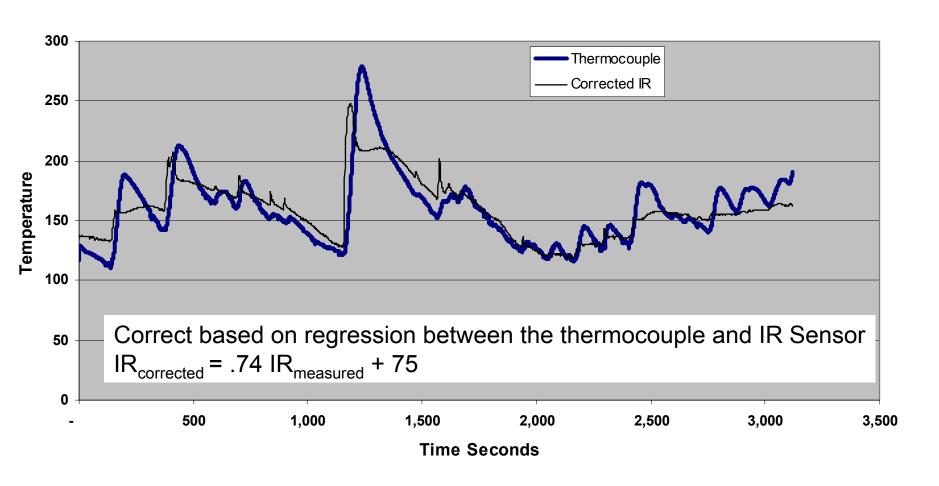
#### Temperature Measurements Made on May 17, 2005, Between Newark, NJ, and Philadelphia, PA – File 051705\_19.ABT



# IR and Thermocouple Time History (Bias compensation)



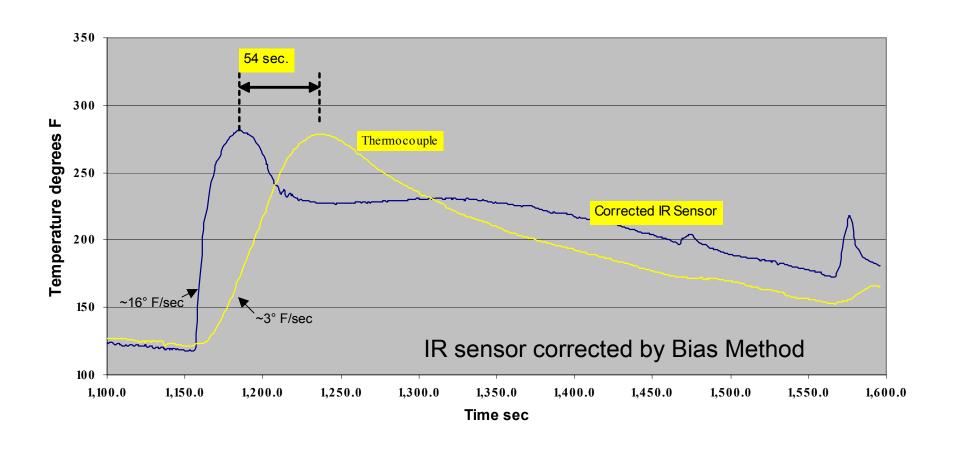
# IR and Thermocouple Time History (Bias compensation)



# Comparison of Thermocouple and IR Sensors During Braking

- The IR Sensor Responds Quickly To Application Of Brakes
- The Thermocouple Requires Significantly More Time
- Peak Temperature Response In Thermocouples Occurs 53 Seconds After Peak In IR Sensor
- See Next Plot

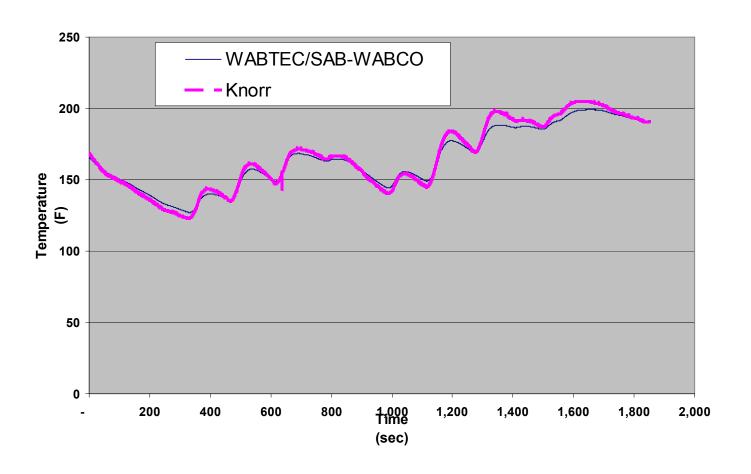
# Difference between IR and Thermocouple Response



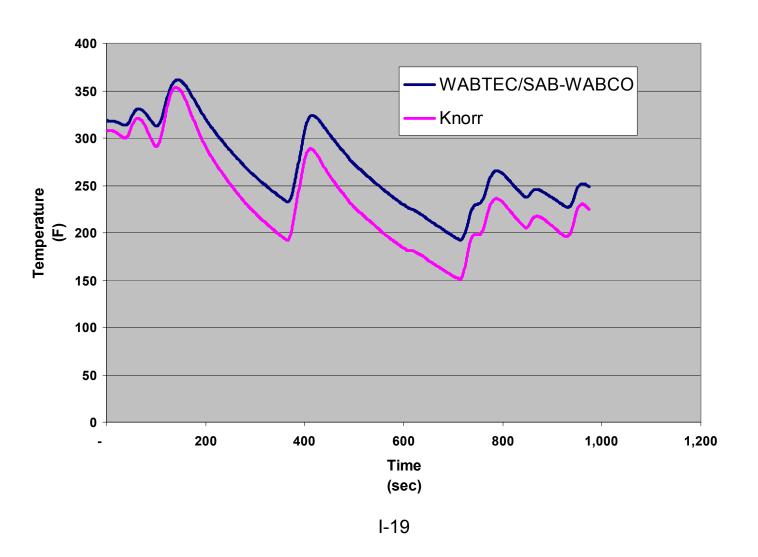
### Testing on June 16 - 18

- The Thermocouples Were The Only Temperature Measurements On The Disc
- Temperature Measurements Were Made On Both The WABTEC/SAB-WABCO And Knorr Discs
- The Next Slide Shows The Recorded Temperatures On The Discs

#### Disc Temperature Measurements – Example 1



### Disc Temperature Measurements – June 16, 2005 – File 061605\_18.AB3

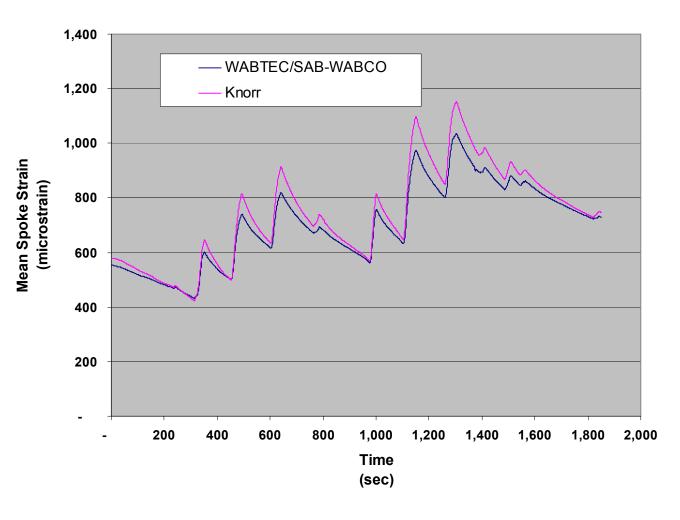


#### Observation

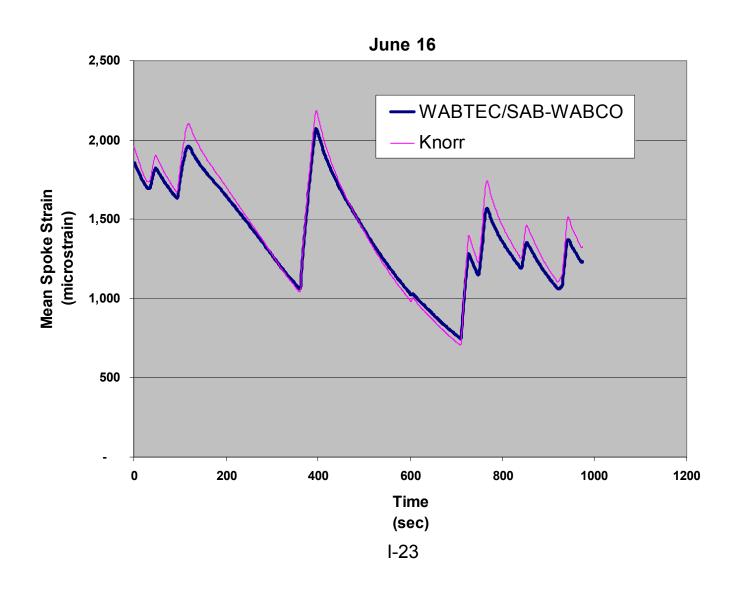
- The Discs Show Similar Temperature Profiles During Testing
- The Knorr Disc Heats Up And Cools Down Just Slightly Faster Than The WABTEC/SAB-WABCO Disc, Both Around 3 °F/Second
- Both Discs Reached A Temperature Of 360 °F, the Highest Seen During Testing

# Spoke Strains and Temperature

### Spoke Mean Strain



### Mean Spoke Strain Measurements – June 16, 2005 – File 061605\_18.AB3



#### Observations

- Both Discs Show Similar Mean Strain Profiles
- The Knorr Disc Shows 3% to 5 % More Mean Strain
- Maximum Mean Strains of 2200 Microstrain were observed for the Knorr Disc
- Maximum Mean Strains of 2100
   Microstrain Were Observed for the WABTEC/SAB-WABCO Disc

## Spoke Mean Strain vs Temperature of Disc Friction Plate

- Temperature Is Measured With Thermocouple Mounted On Back Side Of Disc Near The Outer Edge Of The Friction Ring
- Strains Are The Average Of Gage Pairs

#### Strain Estimates Based on Temperature

- Analysis conducted to estimate the amount of spoke tensile strain per friction plate temperature increase
- This approach used temperature and strain measurements at the beginning of each braking event over a full testing day
- While the new values are lower than the initial estimates, the relationship of the Knorr and WABTEC/SAB-WABCO Discs remained the same
- The Knorr Disc shows about 10% more strain than the WABTEC/SAB-WABCO Disc

#### Spoke Strain/Disc Temperature

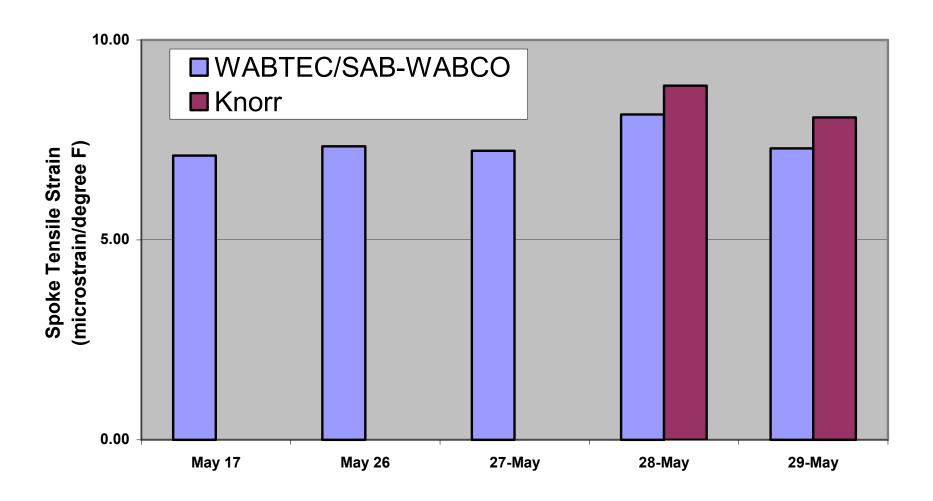
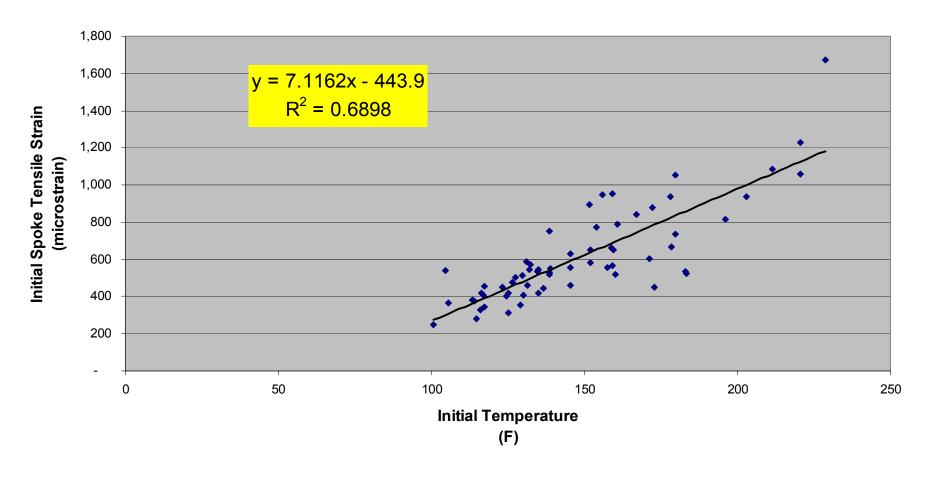


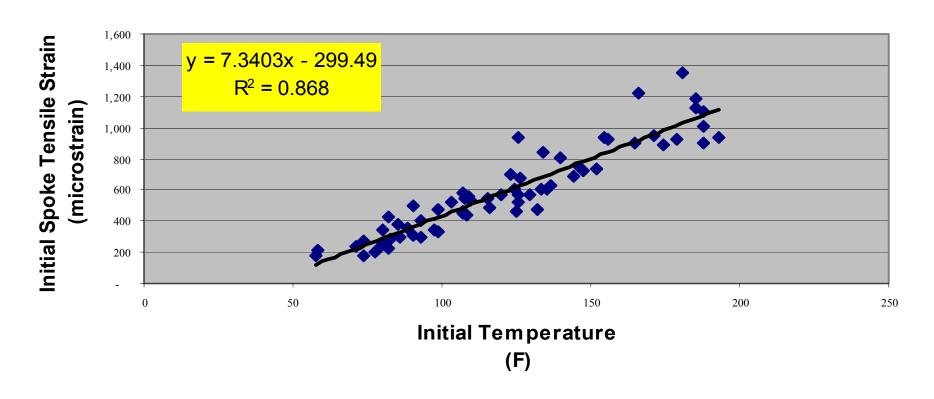
Table I.2. Summary of Strain Estimates Per Degree in Temperature

	Spoke 6 Tensile Strain Microstrain/°F	
	WABTEC/SAB -WABCO	Knorr
May 17	7.11	N/A
May 26	7.34	N/A
May 27	7.23	N/A
June 17	8.14	8.86
June 18	7.29	8.06

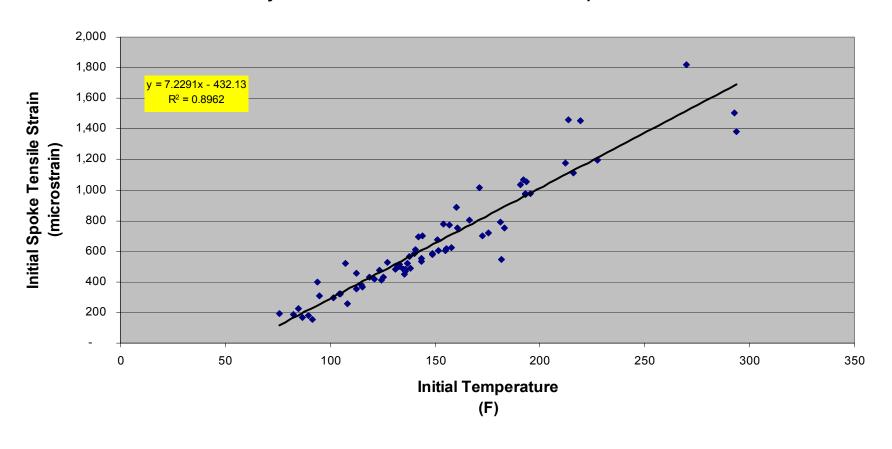
May 17 Center WABTEC/SAB-WABCO Disc Spoke 6



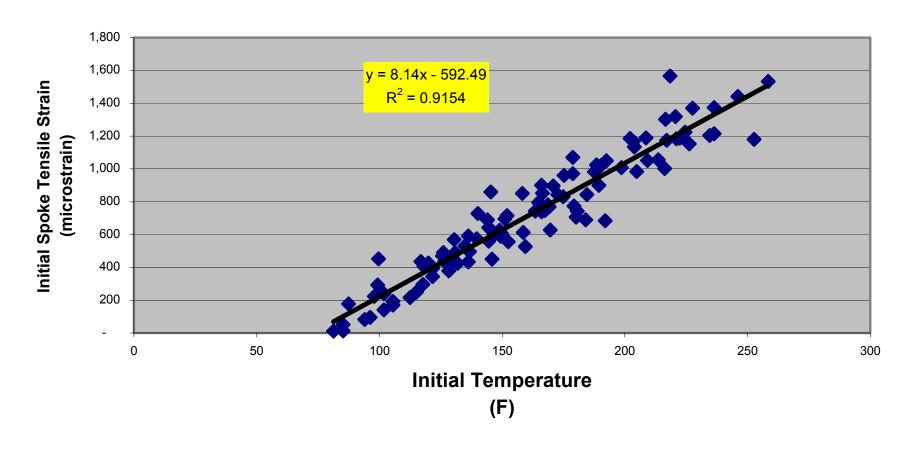
May 26 Center WABTEC/SAB-WABCO Disc Spoke 6



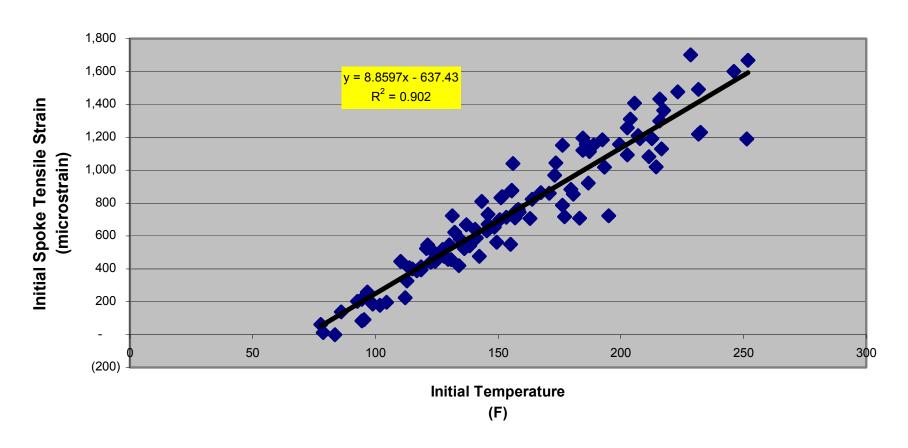
May 27 Center WABTEC/SAB-WABCO Disc Spoke 6

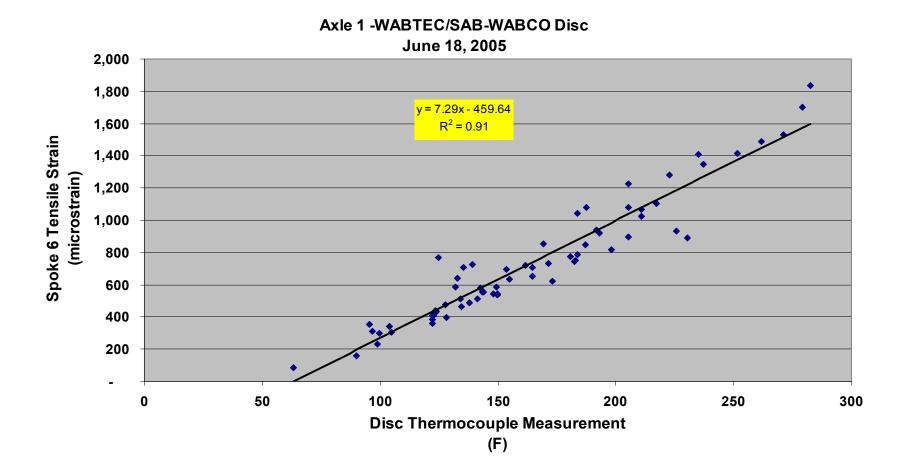


June 17 Center WABTEC/SAB-WABCO Disc Spoke 6

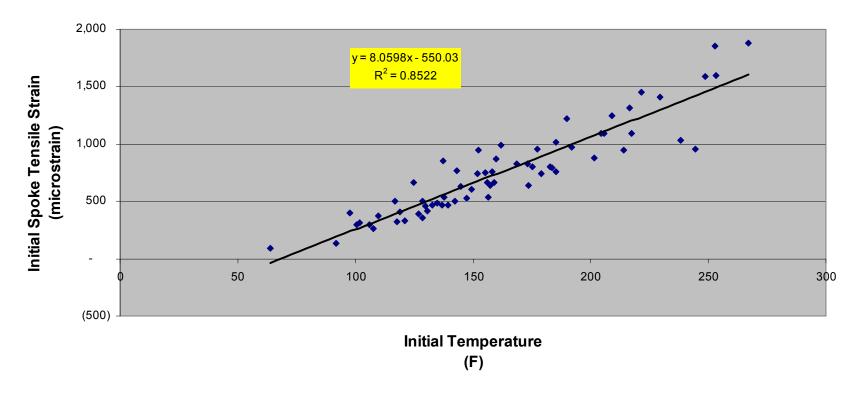


June 17 Center Knorr Disc Spoke 6





Axle 2 -Center Knorr Disc June 18, 2005

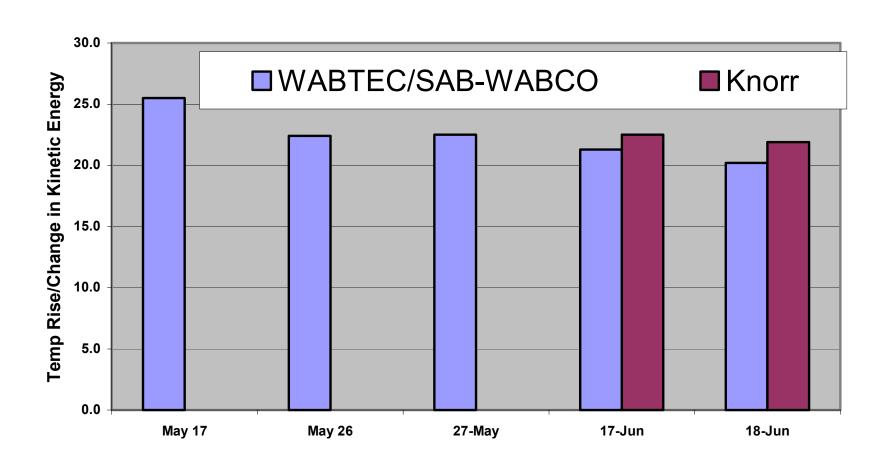


# Heating and Cooling of Discs

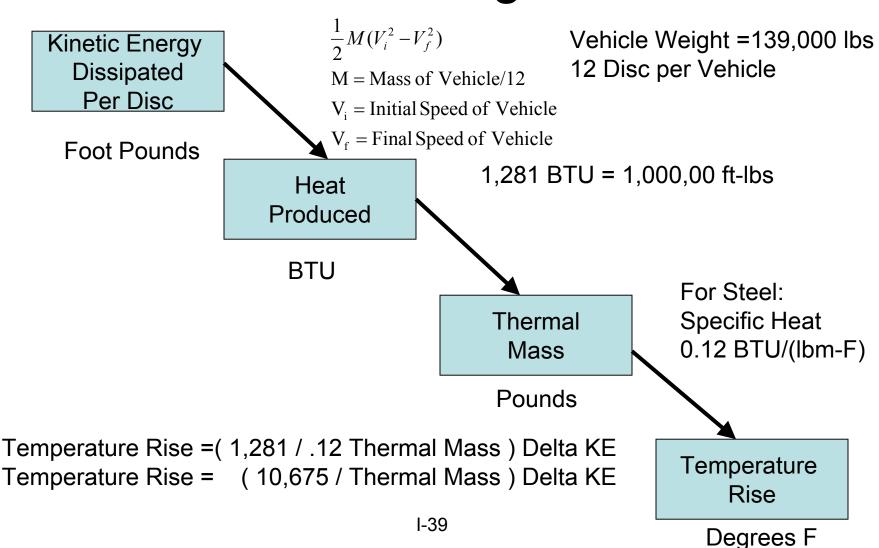
# Heating of Discs

- Based On A Limited Number Of Braking Sequences, It Was Observed That The Knorr Disc Heated Up More Than The WABTEC/SAB-WABCO Disc During Braking
- A Methodology To Quantify This
   Difference Was Developed To Include All
   Braking Sequence Days For Which
   Temperature Data Was Observed

### Temperature Rise



# Disc Temperature Rise Due to Braking



#### **Temperature Build-up During Braking**

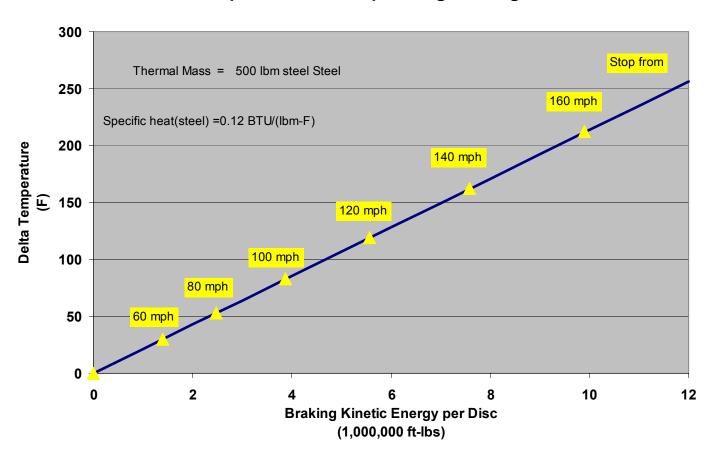
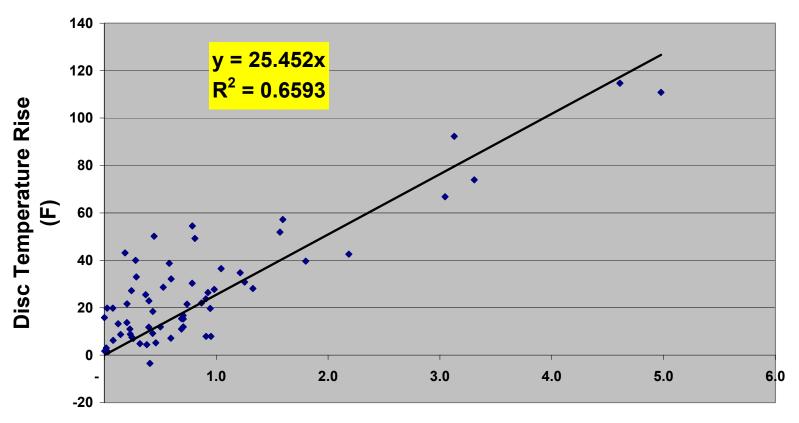


Table I.3. Summary, Disc Temperature Rise for Change in Kinetic Energy Table

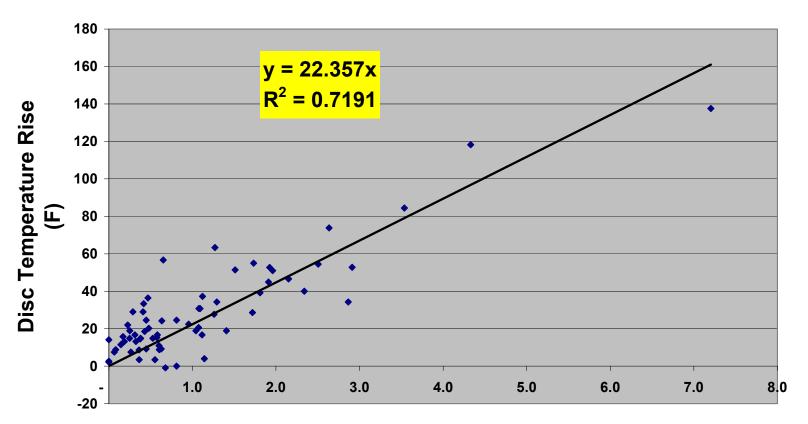
	Disc Temperature Rise for Change in Kinetic Energy TC <sub>ke</sub>		
	WABTEC/SAB -WABCO	Knorr	
<b>May 17</b>	25.5	N/A	
May 26	22.4	N/A	
May 27	22.5	N/A	
June 17	21.3	22.5	
June 18	20.2	21.9	

CT<sub>ke</sub> - May 17 - Center WABTEC/SAB-WABCO Disc



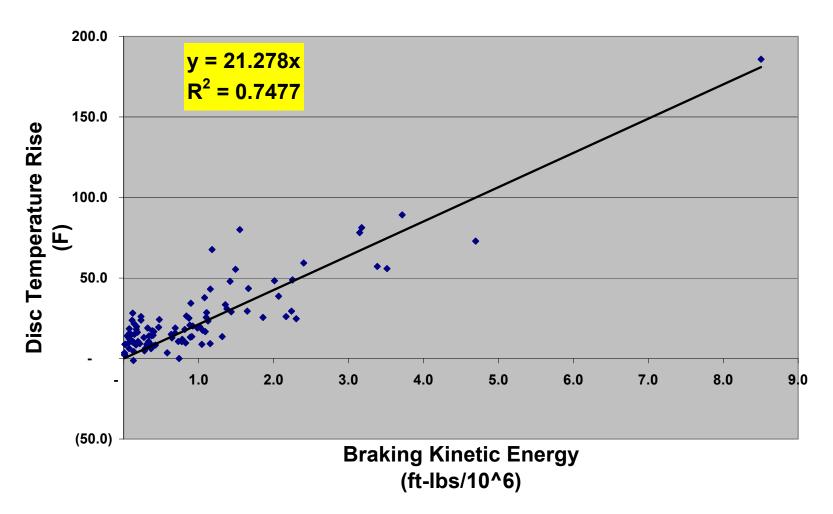
Braking Kinetic Energy (ft-lbs/10^6)

CT<sub>ke</sub> - May 26 - Center WABTEC/SAB-WABCO Disc

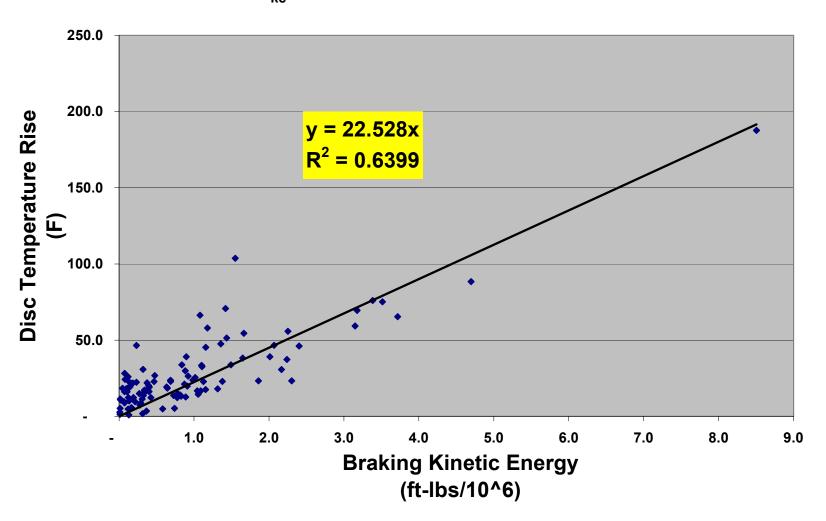


Braking Kinetic Energy (ft-lbs/10^6)

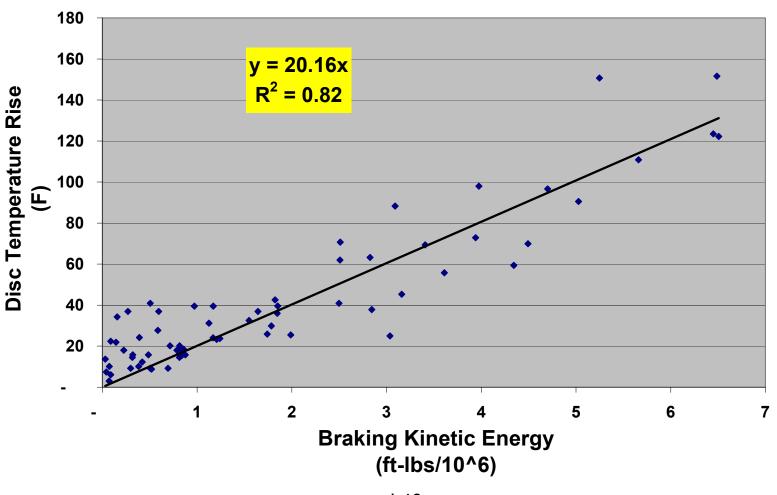
CT<sub>ke</sub> - June 17 - Center WABTEC/SAB-WABCO Disc



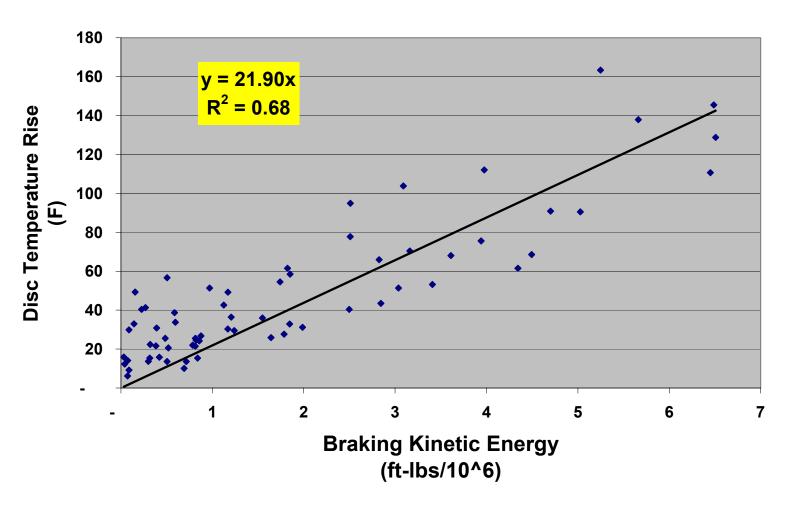
CT<sub>ke</sub> - June17 - Center Knorr Disc



CTke - June 18 - Center WABTEC/SAB-WABCO Disc



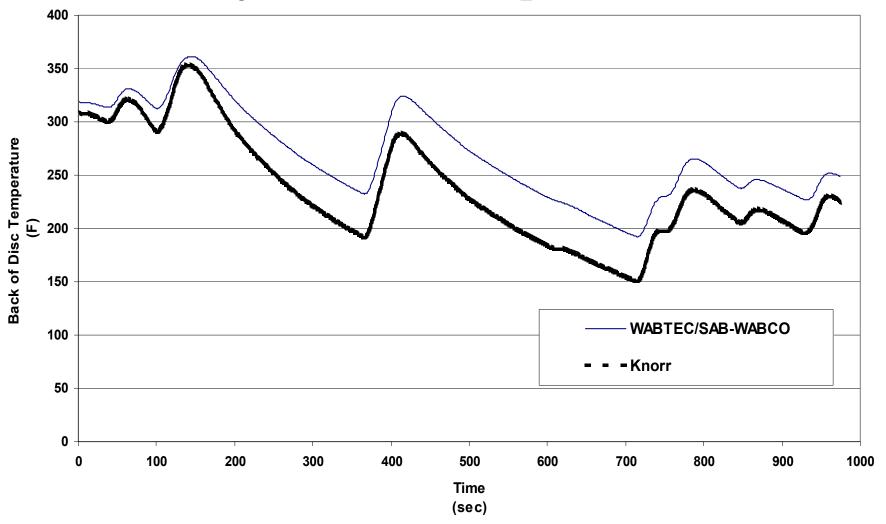
CTke - June 18 - Center Knorr Disc



# Cooling of Discs

- Analysis Conducted To Address The Time Constants For The WABTEC/SAB-WABCO And Knorr Disc Under The Same Operational Conditions
- The Knorr Disc Cool Down Faster Than The WABTEC/SAB-WABCO Disc, While The Knorr Disc Heats Up Faster During Braking Cycles

#### Temperature Profile of WABTEC/SAB-WABCO and Knorr Brake Discs During Shakedown Run, File 061605\_18.AB3 - June 16, 2005



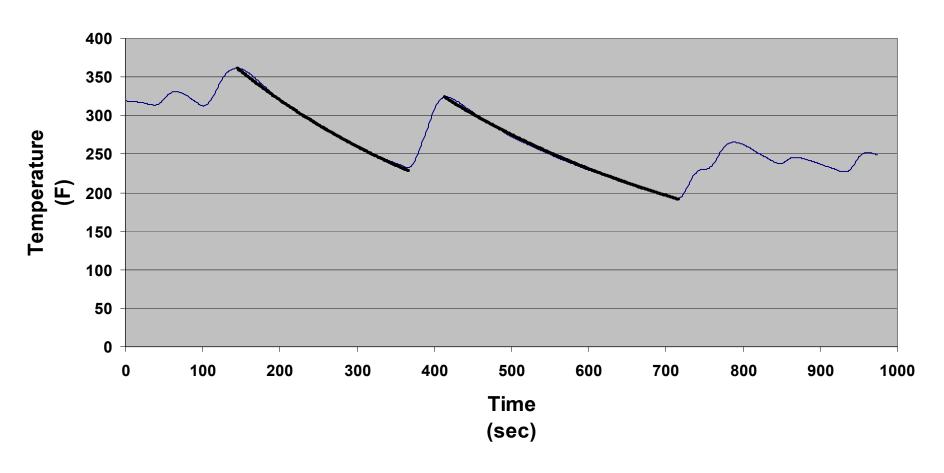
### Table I.4. Thermal Time Constants

Observation		Initial Temperature		Time Constant		
Event	Period	WABTEC/ SAB-WABCO	Knorr	WABTEC/SAB- WABCO	Knorr	Ratio
1	221	361	352	355	251	71%
2	303	324	289	400	299	75%

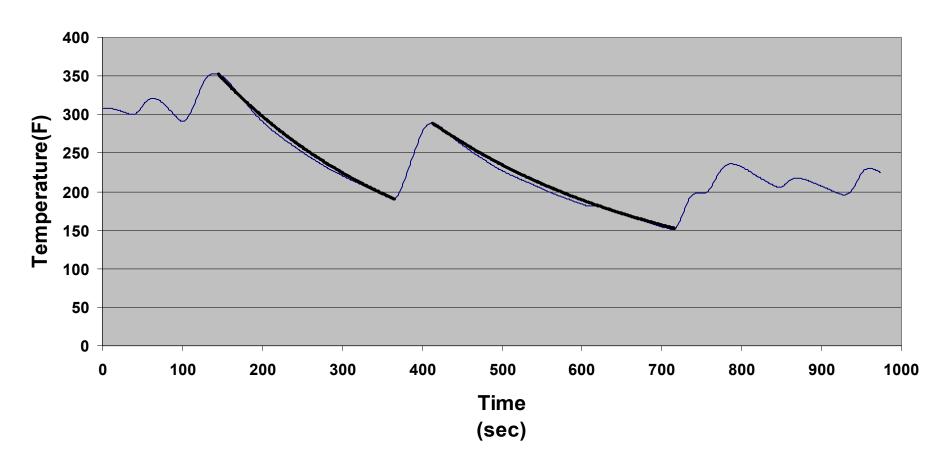
Average 377 275 73%

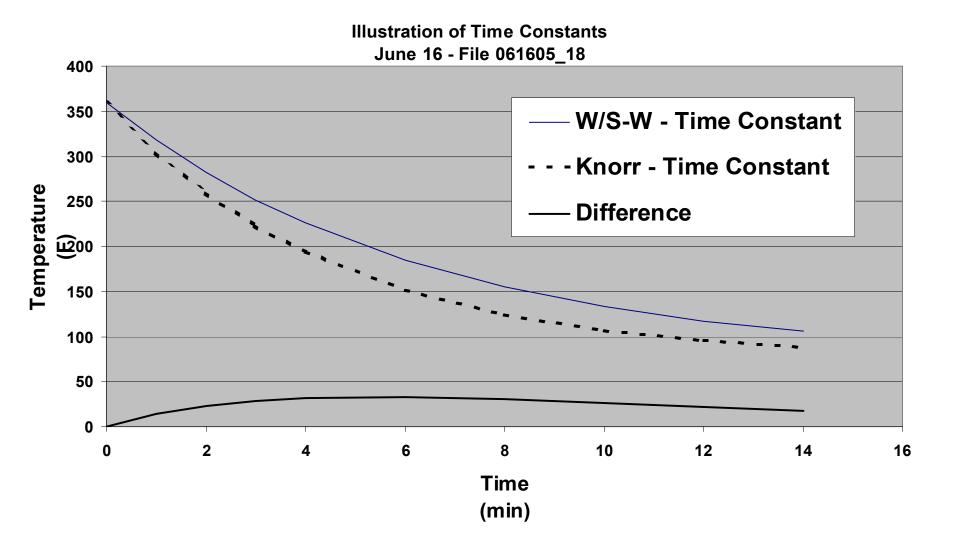
Time Constant (minutes) 6.3 4.6

### Back of Disc Temperature, WABTEC/SAB-WABCO Disc June 16 - File 061605\_18

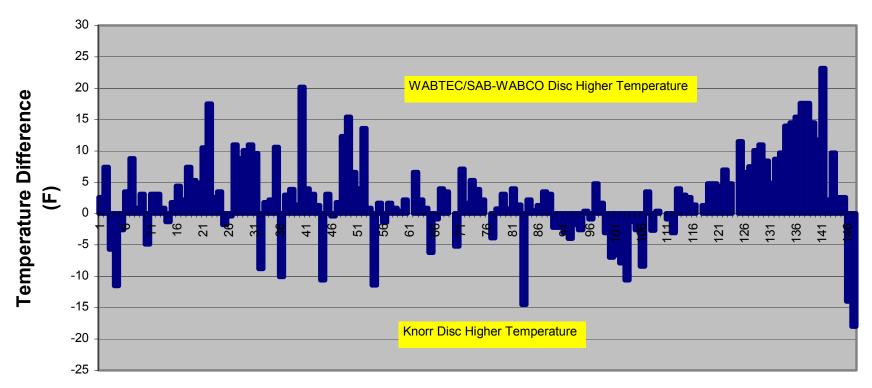


Back of Disc Temperature, Knorr Disc June 16 - File 061605\_18





#### **Temperature Differences After Braking Events - June 17, 2005**



**Braking Sequence**